ENERGY
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A COST/BENEFIT ANALYSIS OF FUEL CYCLE COSTS ASSOCIATED WITH USING PYROPROCESSING AND INTEGRAL FAST REACTORS TO CONSUME SPENT NUCLEAR FUEL

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Background on U.S. Waste Inventories and the Waste Management Program

In the United States ("U.S."), there are a total of 100 operating commercial nuclear power plants ("NPP") that produce an estimated 2,000 metric tons of uranium ("MTU") of spent nuclear fuel ("SNF") annually. In addition to the current fleet of 100 NPPs, there are an additional 19 NPPs that have permanently ceased operation, some of which have been dismantled and others of which are awaiting final dismantling and decommissioning. All of these 19 shutdown NPPs continue to store SNF onsite. Five nuclear power reactors are under construction in the U.S. and are expected to be operational between 2015 and 2020. Including these new plants, an estimated total of 140,000 MTU of commercial SNF will be discharged over the next 70 years.[1] There is also an estimated 10,000 MTU of SNF and high-level radioactive waste ("HLW") from U.S. defense programs – bringing the total quantity of waste requiring disposal to an estimated 150,000 MTU.

The *current* nuclear fuel cycle in the U.S. is known as a "once-through" cycle, because nuclear fuel is irradiated in commercial NPPs to generate electricity, and then is slated for disposal as waste without any recycling for reuse. Under the Nuclear Waste Policy Act ("NWPA"), the capacity of the first repository is limited to 70,000 MTU, of which civilian SNF would have a 60,000 MTU share with the additional 10,000 MTU of capacity being devoted to disposal of SNF and HLW from defense programs. Due to the large quantity of commercial and defense waste anticipated to be disposed of in the U.S. over the next 70 years (150,000 MTU), more than one repository will be necessary.

Many obstacles stand in the way of developing and executing a long-term strategy for disposal of SNF in the U.S. After many years of program delays, the Yucca Mountain repository project was halted in 2010 with the suspension of the U.S. Nuclear Regulatory Commission's ("NRC") review of the Yucca Mountain License Application ("LA"). While the NRC has resumed its review of the Yucca Mountain LA, restart of the Yucca Mountain project is considered unlikely in the current political climate.

If the Yucca Mountain project is not resurrected and the repository program restarted, then a complete overhaul of the U.S. waste program will be required including new legislation; a new repository siting process; a search for one or more sites for disposal; and development, licensing, construction and operation of permanent disposal facilities. Given the history of the U.S. waste program, it could be decades before a geologic repository begins operation in the U.S. In the interim, SNF inventories at NPP sites and the federal government's liability associated with its failure to remove SNF from commercial NPP sites continue to grow.

1 This assumes that the majority of the existing and new plants will operate for 60-year license terms, resulting in new plants reaching the end of 60-year license terms within the next 70 years.

EXECUTIVE SUMMARY

Results of Study

Within the context of long-term waste management and sustainable nuclear fuel supply, there continue to be discussions regarding the future path that the U.S. should take in its research and development activities associated with advanced fuel cycles, including development of advanced recycling technologies. The current once-through fuel cycle used in the U.S., in which SNF is treated as waste and directly disposed of in deep geologic repositories without recycling, is not an efficient use of a valuable resource; namely, the uranium and other reusable components in SNF.

Deploying “pyroprocessing” technology and Integral Fast Reactors (“IFRs”) to recycle the current inventory of commercial uranium oxide (“UO_2”) SNF provides a number of significant, potential benefits, key among these are: avoiding the need for additional costs associated with a second repository by reducing the overall volume of radioactive waste requiring geologic disposal; reducing the radiotoxicity and heat load of the final commercially-generated waste form to be disposed, which would reduce the cost of the design and construction of the single geologic repository needed for nuclear waste; and the ability to pay for pyroprocessing/IFR costs by the avoided cost of a second repository. In addition, if a large-scale pyroprocessing facility and a fleet of IFRs are able to be deployed sooner than a geologic repository, then there also may be avoided costs associated with the government’s liability for the Department of Energy’s (“DOE”) failure to begin SNF acceptance in 1998. Deployment of pyroprocessing and IFRs also will help to conserve uranium resources, thereby prolonging the use of nuclear energy if uranium supplies become scarce or the price of uranium increases significantly.

As noted above, under the NWPA, the expected 150,000 MTU inventory of commercial and defense SNF and HLW would require that at least two repositories be built. If the current U.S. inventory of commercial light-water reactor (“LWR”) SNF is pyroprocessed and the plutonium and minor actinides[2] from this SNF are recycled in IFRs, the resulting HLW will have a significantly lower volume and heat load than the original SNF. The amount of repository space required for disposal of SNF and HLW is a function of the volume and heat load of the emplaced SNF or HLW. As a result of pyroprocessing the existing SNF inventory, significant reductions in the volume of material to be disposed can be realized and the need to construct a second repository *can be avoided*. Based on recent cost estimates conducted by the DOE, development and operation of a geologic repository

2 The minor actinides are the actinide elements in used nuclear fuel other than uranium and plutonium (which are termed the major actinides). The minor actinides include neptunium, americium, curium, as well as other elements. Plutonium and the minor actinides are the greatest contributors to SNF radiotoxicity and heat generation during the period of 300 to 20,000 years following SNF discharge.

for disposal of the projected 140,000 MTU of commercial SNF would range from $24 billion to $81 billion, and higher costs would likely be incurred to fabricate disposal canisters, repackage SNF from existing dual-purpose canisters, and provide consolidated interim storage. To put the recent DOE estimate into perspective, a 2008 cost estimate for the Yucca Mountain repository was $96.2 billion for disposal of only 70,000 MTU of SNF and HLW in a single repository – higher than the recent DOE cost estimate for disposal of 140,000 MTU of SNF. If the need for a second repository is avoided, then as a result of that alone, the cost savings attributed to pyroprocessing and IFRs could be $12 billion to $96 billion, or higher.

Recommendation

There are significant potential cost savings and technical benefits associated with recycling nuclear fuel (*i.e.*, developing pyroprocessing and IFRs), compared to the current once-through fuel cycle. Key among these is eliminating the need for a second geologic repository at a cost savings in the range of $12 to $96 billion.

However, adequate research and development funding, and deploying a pilot facility to demonstrate pyroprocessing in the U.S. is an important step in resolving remaining technical challenges prior to scaling up the technology to a commercial scale. Expanded research, development, and demonstration of pyroprocessing and IFR technology should continue in the U.S. to provide a sustainable alternative program for long-term waste management and nuclear power deployment.

1. INTRODUCTION

1.1 Background

In the United States ("U.S."), there are a total of 100 operating commercial nuclear power plants ("NPP") that produce an estimated 2,000 metric tons of uranium ("MTU") of spent nuclear fuel ("SNF") annually. In addition to the current fleet of 100 NPPs, there are an additional 19 NPPs that have permanently ceased operation, some of which have been dismantled and others of which are awaiting final dismantling and decommissioning. All of these 19 shutdown NPPs continue to store SNF onsite. Through December 2013, an estimated inventory of 72,000 MTU of SNF from these reactors has been generated. Five nuclear power reactors are under construction in the U.S. and are expected to be operational between 2015 and 2020. Including these new plants, an estimated total of 140,000 MTU of commercial SNF will be discharged over the next 70 years[3] – double the current inventory. There is also an additional estimated 10,000 MTU of SNF and high-level radioactive waste ("HLW") from U.S. defense programs – bringing the total quantity of waste to an estimated 150,000 MTU. Commercial SNF is stored in water-filled pools that are adjacent to the nuclear power reactors or, after several years of cooling, in dry cask storage facilities at NPP sites until it can be shipped off site for processing, consolidated interim storage or disposal. The current nuclear fuel cycle in the U.S. is known as a "once-through" cycle, because nuclear fuel is irradiated in commercial nuclear reactors to generate electricity, and then is slated for disposal as waste without recycling for reuse.

Due to the current debate surrounding the Yucca Mountain repository program, there is considerable uncertainty in the U.S. regarding the schedule for acceptance of SNF by the Department of Energy ("DOE") as required by the Nuclear Waste Policy Act of 1982, as amended ("NWPA").[4] While the DOE put forth a new long-term waste management strategy in early 2013, this new strategy will require Congressional action to amend the NWPA, followed by an uncertain process and schedule for siting waste management facilities. In the interim, SNF inventories at NPP sites and the federal government's liability associated with its failure to remove SNF from commercial NPP sites continue to grow. DOE anticipates spending $24 billion to $81 billion to build one or more geologic repositories for SNF.[5] The daunting task of siting and operating more than one repository

3 This assumes that the majority of the existing plants plus new plants will operate for 60-year license terms, resulting in new plants reaching the end of 60-year license terms within the next 70 years.

4 The NWPA mandated the development of a first repository at Yucca Mountain with a disposal capacity of 70,000 MTU of commercial and defense SNF and high-level radioactive waste ("HLW"). The civilian SNF share of the first repository was estimated to be 60,000 MTU. Based on the projected 140,000 MTU of civilian SNF expected to be discharged from current and planned nuclear power plants in the U.S., a second repository, with a capacity of at least 80,000 MTU would be necessary to dispose of the remaining civilian SNF.

5 As discussed in Section 3.3, this estimate was based on a January 2013 DOE cost study of repository alternatives for the disposal of 140,000 MTU of SNF with costs that ranged from approximately $24 billion to $81 billion in 2012 dollars – more than a 200% difference in costs. Even higher costs are possible if additional SNF packaging is necessary at a repository, if consolidated storage is deployed, or if SNF must be

may help to shift the U.S. focus to recycling and fuel cycle technologies that will reduce the quantities of waste requiring disposal as well as reduce the toxicity of the waste.

If a pyroprocessing facility can be deployed on an earlier schedule than permanent disposal facilities and begin accepting SNF from U.S. NPPs at an earlier date, then there may be additional avoided costs associated with DOE's liability for failure to begin SNF acceptance in 1998. One alternative to the current once-through fuel cycle is to separate the waste in UO_2 SNF requiring disposal from other materials in the SNF, such as uranium, that then could be recycled as fuel for subsequent reuse in a "fast reactor." The recycling and reactor technologies discussed in this Report are pyroprocessing and the Integral Fast Reactor ("IFR").

1.2 Purpose of Report

Within the context of long-term waste management and sustainable nuclear fuel supply, there continue to be discussions regarding the future path that the U.S. should take in its research and development activities associated with advanced fuel cycles, including development of advanced recycling technologies. The current once-through fuel cycle used in the U.S., in which SNF is treated as waste and directly disposed of in deep geologic repositories without recycling, is not an efficient use of a valuable resource; namely, the uranium and other reusable components in SNF.

This Report compares fuel cycle costs associated with the current once-through fuel cycle ("OT Cycle") for commercial light-water reactors ("LWR") which use uranium dioxide ("UO_2") fuel, with a fully-closed fuel cycle in which the SNF from the OT Cycle as well as FR SNF is recycled through pyroprocessing into new metallic fuel for use in IFRs ("FR Cycle").[6] In addition to examining fuel cycle costs for the two fuel cycles, this Report provides a comparison of key parameters associated with the two fuel cycles including: waste volumes requiring disposal, and heat load and activity of the waste requiring disposal, which affect the number of geologic repositories needed and the design and cost of those repositories.

To support continued discussions about the next phase for developing an integrated fuel cycle with pyroprocessing and IFRs, this Report also examines the benefits and costs associated with developing a 2,000 metric ton heavy metal ("MTHM") per year pyroprocessing plant for processing the existing U.S. LWR SNF inventories.

repackaged.

6 Calculation of fuel cycle costs are based on a model developed by the Organization for Economic Co-operation and Development (OECD) Nuclear Energy Agency ("NEA"), an international organization that is based in France and of which the U.S. is a member. The NEA model, "Steady-State Analysis Model for Advanced Fuel Cycles Schemes" ("SMAFS"), was utilized in an NEA 2006 assessment entitled "Advanced Fuel Cycles and Radioactive Waste Management." ["NEA 2006"]

Pyroprocessing allows recycling of the SNF as metallic IFR fuel, reduces the long-term toxicity of the SNF, significantly reduces the size of a first geologic repository, and could eliminate the need for a second repository.

Section 2 provides an overview of the model used to calculate fuel cycle costs in this study, including key input parameters and key output parameters. Fuel unit cost components, waste management cost components, and reactor capital costs that are used in this study are summarized in Section 2, with more detail regarding the bases for these unit costs provided in Appendix A. Unit costs include nominal costs and lower and upper bounding values for each cost component. Section 2 also provides the basis for the conclusions that pyroprocessing and IFRs can eliminate the need for a second permanent geologic repository and produce very substantial cost savings.

Section 3 provides an overview of the OT Cycle including fuel cycle, waste management, and electricity generation costs using the nominal unit cost values discussed in Section 2 and Appendix A. A summary of waste management volumes for a OT Cycle, including identification of key waste management parameters is provided. Uncertainties regarding long-term disposal costs for the OT Cycle are also identified.

Section 4 provides an overview of the FR Cycle including a high-level description of pyroprocessing and IFRs that would be used to close the existing fuel cycle. FR fuel cycle, waste management, and electricity generation costs are identified using the nominal unit cost values discussed in Section 2. In addition, a cost analysis of a 2,000-ton pyroprocessing plant is summarized including the results of a sensitivity analysis of financial parameters concerning construction and operation of such a plant.

Section 5 provides a comparison of the OT Cycle and FR Cycle waste management parameters. Conclusions regarding transition to a FR Cycle are discussed in Section 6.

Appendix A provides a summary of the unit cost assumptions used in this analysis from the SMAFS model, including the nominal, lower-bound and upper-bound unit costs. Appendix B summarizes a comparison of the OT Cycle and FR Cycle nominal costs. Appendix C provides a list of acronyms.

2. METHODOLOGY

This section begins with an overview of the "SMAFS" model used to calculate fuel cycle costs in this study, including key input and output parameters. Assumptions associated with the fuel unit cost components, waste management cost components, and reactor capital costs that are used in this study are provided in Appendix A. Unit costs include nominal costs and lower and upper bounding values for each cost component.

This section then discusses the approach and assumptions used to develop the analysis regarding the number of permanent geologic repositories needed, and associated costs.

2.1 Description of The SMAFS Fuel Cycle Cost Model

The SMAFS model that ERI uses in this analysis was developed by NEA researchers to analyze the impact that advanced fuel cycles might have on waste management policies. It was designed to provide not only a comparison of the relative economics of different fuel cycles, but also to compare other key fuel cycle and waste management indicators. The SMAFS model has been utilized by ERI in the past to perform evaluation and comparison of multiple fuel cycles and it has been utilized by international agencies such as the Korean Atomic Energy Research Institute ("KAERI").

The key fuel cycle and waste management indicators that are used in comparing different fuel cycles, include the following:

- Fuel cycle cost – this indicator includes front-end costs (uranium, enrichment and fuel fabrication) as well as back-end waste management costs.
- Total generation cost – this indicator includes the fuel cycle and waste management costs as well as the capital, investment, and operating costs of the nuclear reactors considered.
- Uranium consumption – this is driven, in part, by the number of IFRs in the fuel cycle scheme considered.
- Activity of the SNF and HLW after 1,000 years – this indicator describes the radioactive source term after the decay of heat generating isotopes in HLW and is indicative of the long-term toxicity of the waste.[7]
- Decay heat of the SNF or HLW after various time periods (e.g., 200 years and 1,000 years) – this indicator is important in the handling, conditioning, and final disposal of SNF and HLW in geologic repositories, and also has consequences for processing and transportation.
- HLW and SNF volume to be disposed – this indicator is of key importance in the number and size of geologic repositories needed for disposal of HLW and SNF.

7 HLW is highly radioactive materials produced as a byproduct of reprocessing of SNF that includes fission products ("FP") from the nuclear fission reaction. HLW may contain other elements such as actinides if these elements are not separated from the FP during reprocessing operations.

2.2 SMAFS Model Input Parameters

In order to calculate the key fuel cycle and waste management indicators discussed above, the following data input parameters are utilized:

Waste generation parameters associated with:

- Front-end of the fuel cycle which includes: mining and milling of uranium, conversion of uranium to uranium hexafluoride, enrichment and fuel fabrication.
- Reactor operation (short-lived [“SL”] and long-lived [“LL”], low and intermediate level waste [“LILW”], and SNF) for LWRs and IFRs.
- Pyroprocessing of UO_2 and IFR SNF including the LILW-SL, LILW-LL, and HLW associated with pyroprocessing.

Unit cost parameters associated with:

- Front-end fuel cycle (mining and milling of natural uranium, conversion, enrichment, and fuel fabrication).
- Reactor investment and operations and maintenance ("O&M") costs.
- SNF transport and storage for UO_2 and IFR fuel types.
- Pyroprocessing of UO_2 and IFR SNF.
- On-site dry storage, packaging, and off-site long-term storage for UO_2 SNF, HLW and other waste products. Long-term storage costs are for materials such as depleted uranium (“DU”) and irradiated uranium (“U_{irr}”)[8.]
- Waste disposal, including LILW-SL, LILW-LL, and SNF and HLW.

Unit costs include a nominal value (“NV”), lower bound (“LB”) and upper bound (“UB”) as summarized in more detail in Appendix A. In addition to the waste generation and cost data, the model also includes mass flows for each fuel cycle considered, and data regarding waste activity, decay heat, and neutron sources for SNF and HLW requiring long-term storage and disposal.

2.3 SMAFS Model Output

The SMAFS model was designed to calculate equilibrium fuel cycle costs assuming that all reactors in a given fuel cycle scheme operate at constant power and that all mass flows have reached an equilibrium. The model calculates the following:

For each fuel cycle scheme, the model output includes:

- SNF and HLW radioactivity measured in Terabecquerel (“TBq”), thermal output in watts (“W”), and neutron source (neutrons/second/group) at time periods of 5, 50, 200, 1000, and 10000 years. These parameters are normalized to units per Terawatt-hour electric (“TWhe”) of electricity generated by NPPs.

8 Irradiated uranium is also referred to as “reprocessed uranium” or “RepU”.

- Fuel cycle and total generation cost, including a detailed breakout of costs for front-end fuel cycle materials; pyroprocessing; reactor investment; reactor O&M; and waste management. Costs are calculated on a mill per KWh ("mill/kWh") basis as well as on a comparative basis among the fuel cycles analyzed.[9]
- Quantities of waste generated requiring disposal for each step of the fuel cycle. This includes: LILW-SL (m^3), LILW-LL (m^3), HLW (m^3), SNF (MTU or MTHM).[10]

2.4 Approach to Repository Need/Cost Analysis

The analysis of the need for permanent geologic repositor[ies], their size, and cost comparisons between the OT and FR Cycles was based on a number of factors. These included the number of commercial nuclear power plants currently operating in the U.S. and the estimated amount of SNF and its constituent products (uranium, plutonium, minor actinides, HLW) produced from those plants. The analysis also considered the number of nuclear power plants that have permanently ceased operations and the amount of SNF stored at these sites, as well as the number of nuclear power plants under construction. The analysis took into account the estimated amount of SNF and HLW from U.S. defense programs. All of these were added together to produce an estimated total quantity of waste requiring permanent geologic disposal over the next 70 years.[11] The sources for this information were based on ERI's internal projections for current installed and estimated future U.S. nuclear capacity, historical SNF and HLW from commercial plants and defense programs, and ERI's projection of SNF expected to be discharged in the future.

In addition, the repository analysis considered the statutory limit on the capacity of the first repository under the NWPA. The SMAFS model was used to produce data on the amount of permanent geologic disposal capacity needed, based upon anticipated volumes under the OT and FR Cycles, as well as heat loads and radiotoxicity, all of which contribute to the number, size and cost of permanent geologic repositor(ies) that are required. Projected costs of building repositories are based upon a January 2013 DOE assessment of the Nuclear Waste Fund ("NWF") fee, "Nuclear Waste Fund Fee Adequacy Assessment Report" as well as a 2008 Total System Life Cycle Cost Estimate for the Yucca Mountain Repository.[12]

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9 The mill is a unit of currency used sometimes in accounting. A mill is equivalent to 1⁄1000 of a U.S. dollar (a tenth of a cent).

10 The term "MTU" refers to metric tons of uranium and is generally used to quantity UO_2 SNF. Other types of SNF, such as metal IFR fuel or mixed-oxide ("MOX") fuel contain nuclear fuel elements other than uranium, such as plutonium or minor actinides. For these other types of SNF, the quantity is typically referred to as metric tons of heavy metal or "MTHM".

11 This assumes that the majority of the existing and new plants will operate for 60-year license terms, resulting in new plants reaching the end of 60 year terms within the next 70 years.

12 U.S. DOE, "Nuclear Waste Fund Fee Adequacy Assessment Report, January 2013. Attachment, Carter, Joe, Savannah River National Laboratory, "Back End Fuel Cycle, Cost Comparison Prepared for U.S. Department of Energy, Nuclear Fuel Storage and Transportation Planning Project, December 21, 2012.

3. THE CURRENT (ONCE-THROUGH) FUEL CYCLE WITH GEOLOGIC DISPOSAL OF SNF

The **OT Cycle** modeled for this Report assumes the use of commercial LWRs and is similar to the current fuel cycle scheme being used in the U.S. The OT Cycle relies on a fuel cycle scheme developed in NEA 2006 that includes the use of 1,450 megawatt-electric ("MWe") Pressurized Water Reactors ("PWR") operating with a 90% capacity factor, conventional UO_2 fuel, and direct disposal of SNF in a geologic repository. This fuel cycle scheme is shown in Figure 1.[13] The OT Cycle is used as the reference fuel cycle for comparison with the FR Cycle, described in Section 4. The quantities of uranium fuel and waste shown are those associated with production of 1 TWhe of electricity using the OT Cycle.

The SMAFS model assumes that UO_2 fuel will have an average enrichment of 4.90 weight percent Uranium-235 ("^{235}U") with a discharge burnup of 60 gigawatt-days per metric ton of uranium ("GWd/MTU"), which is typical of large U.S. PWRs.[14] SNF is assumed to be cooled in the spent fuel storage pool for five years prior to dry storage. The SNF is assumed to remain in dry storage for a period of 50 years prior to disposal.

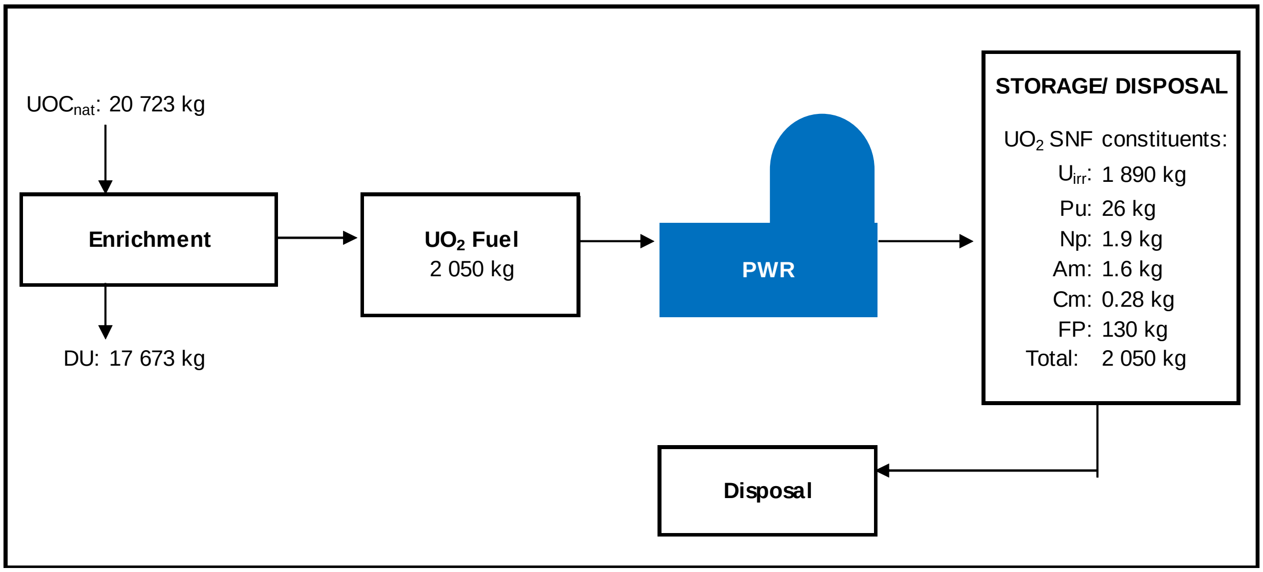

Figure 1 Once-Through Fuel Cycle

U.S. DOE, "Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007," DOE/RW-0591, July 2008.

13 Some of the abbreviations used in Figure 1 are explained in the following sections of this Report.

14 In the U.S., most large PWRs utilize fuel with enrichment levels between 4.5 and 4.95 weight percent ^{235}U. An assumed enrichment of 4.9 weight percent ^{235}U is consistent with current practice.

3.1 Overview of the Front-End of the OT Cycle

The front-end of a OT Cycle includes a number of steps that are necessary to produce fabricated UO_2 fuel for the reference PWR. These steps include production of natural uranium ore concentrates ("UOC"), conversion of UOC into uranium hexafluoride ("UF_6"), enrichment of the ^{235}U isotope in UF_6, and fuel fabrication. UOC are produced through mining and milling to convert uranium ore into U_3O_8 or through other uranium extraction processes. UOC is typically measured in either pounds or short tons of U_3O_8, kilograms uranium ("kgU"), MTU, or tonnes U. UOC is purified and converted to natural UF_6 to prepare it to be processed at uranium enrichment plants. UF_6 is usually measured in kilograms or metric tons of uranium (kgU or MTU) as UF_6.

Natural UF_6 is enriched to obtain the desired enrichment concentration for LWR fuel, usually in the range of 3 to 5 weight percent of the fissile ^{235}U isotope. Natural uranium has a concentration of 0.711 weight percent ^{235}U. The enrichment process also generates a waste stream whose concentration of ^{235}U is depleted (lower than that of natural uranium), known as the "tails" or DU. The assay of ^{235}U in the tails is variable, generally falling between 0.2 weight percent and 0.3 weight percent. The enrichment process is measured in units known as tonnes of separative work or separative work units ("SWU").

The enriched UF_6 is converted to solid UO_2 and then fabricated into fuel pellets that are contained in fuel rods. A specific number of these fuel rods are combined in a square array to form a fuel assembly suitable for use in a specific reactor. Fabricated fuel is typically measured in kgU or MTU contained in UO_2.

Once fabricated, nuclear fuel assemblies will reside in a nuclear reactor for three to four cycles until the assemblies are no longer efficient for the production of electricity. At this point in the OT Cycle, the fuel is considered to be SNF and it is stored in water-filled spent fuel storage pools or in dry cask storage at NPP sites pending permanent disposal.

3.2 Waste Streams Associated with OT Fuel Cycle in the U.S.

The OT Cycle produces DU during the enrichment process. As shown in Figure 1, the enrichment of 20,723 kg of natural UOC results in 18,673 kg of DU, which is assumed to be stored for future use or disposal. Also as shown in Figure 1, a quantity of 2,050 kgU of UO_2 SNF, which is derived from 20,723 kg of natural UOC, is comprised of a number of constituents: U_{irr}, Plutonium ("Pu"), minor actinides[15] (Neptunium ("Np"), Americium ("Am"), Curium ("Cm")), and fission products ("FP"), as shown in Table 1, below. U_{irr} makes up 92.2% of the SNF, FPs are an estimated 6.3%, and Pu and minor actinides are 1.5% as shown in Table 1.

15 The minor actinides are the actinide elements in used nuclear fuel other than uranium and plutonium (which are termed the major actinides). The minor actinides include neptunium, americium, curium, as well as other elements. Plutonium and the minor actinides are the greatest contributors to SNF radiotoxicity and heat generation during the period of 300 to 20,000 years following SNF discharge.

Table 1 Composition of UO_2 SNF To Produce 1 TWhe

UO_2 SNF Constituents	Quantity (kg)	Percent of SNF
Irradiated uranium	1,890	92.2%
Plutonium	26	1.3%
Minor Actinides	3.78	0.2%
Fission Products	130	6.3%
Total	2,050	100%

The SMAFS model includes assumptions regarding volumes of LILW, HLW, and SNF produced during the front end of the nuclear fuel cycle, during reactor operations, and during waste disposal operations. The volume of SNF of 1.5 m^3/TWhe, shown in Table 2, is based on an assumption that 1 MTHM of fuel is equivalent to 0.72 m^3, based on the dimensions of a typical PWR fuel assembly. In addition to the SNF produced, a total of 14.7 m^3 of LILW-SL and 0.3 m^3 of LILW-LL would be produced. Since SNF is disposed of directly in the OT Cycle, no HLW is produced. The parameter, "SNF repository excavation", represents the volume of earthen material that must be excavated to dispose of SNF for a given repository design. It is based on the decay heat load of the SNF, as discussed in more detail in Appendix A. To dispose of the 1.5 m^3 of SNF needed to produce 1 TWhe, 86.5 m^3 of earth would have to be excavated, based on the decay heat (kW)of the SNF.

Table 2 Key Waste-Related Parameters Associated with the OT Cycle

Waste-Related Parameter	Volume
LILW-SL (m^3/TWhe)	14.7
LILW-LL (m^3/TWhe)	0.3
HLW (m^3/TWhe)	0
SNF (m^3/TWhe)	1.5
SNF Repository Excavation (m^3/kW)	86.5
In addition to the above LILW, HLW, SNF and disposal excavation volume, 18,673 kg of DU require storage and/or disposal.	

3.3 U.S. Long-Term Waste Management Program Uncertainties

After many years of program delays, the Yucca Mountain repository project was halted in 2010 with the suspension of the NRC's review of the Yucca Mountain License Application ("LA") and the subsequent appointment of the Blue Ribbon Commission on America's Nuclear Future ("BRC"). In January 2010, the U.S. Secretary of Energy established the BRC to provide recommendations to DOE regarding long-term waste management alternatives for the U.S. The BRC's Final Report to the Secretary of Energy was submitted in January 2012. In that report, the BRC described eight elements that comprise its recommended strategy. While the BRC's recommendations included a number of elements to advance the U.S. waste program, no concrete action has been taken by the U.S. Congress or the Administration and the U.S. waste management program remains in limbo with U.S. NPPs facing the prospect of very long-term dry storage of SNF – possibly for decades after plants cease production of electricity. In November 2013, in response to an August 2013 decision by the U.S. Court of Appeals for the D.C. Circuit ("DC Circuit") which ordered NRC to continue its review of the Yucca Mountain LA, U.S. Nuclear Regulatory Commission ("NRC") Commissioners ordered the NRC staff to complete and publish safety evaluation reports regarding the LA for the proposed Yucca Mountain repository consistent with available resources.

In addition to the uncertainty regarding the path forward for disposal of SNF in the U.S., there is even greater uncertainty regarding the cost for disposal of SNF. In response to litigation by the nuclear industry and electric utility state regulatory agencies that prompted a Federal Court to order DOE to issue a new assessment of fees for disposal of SNF, DOE issued an updated cost estimate for development of geologic disposal in the U.S. in January 2013. DOE's updated assessment concluded that "neither insufficient nor excess revenues are being collected" to recover the federal government's waste disposal costs and therefore did not propose any adjustment to the current fee. This estimate was based on a cost study of repository alternatives for the disposal of 140,000 MTU of SNF with costs that ranged from approximately $24 billion to $81 billion in 2012 dollars – more than a 200% difference in costs. Even higher costs are possible if additional SNF packaging is necessary at a repository (a likely scenario given that the current dry storage packaging used at NPP sites hold between 9 and 15 MTU of SNF – compared with some repository concepts with waste package capacities of 2 MTU). DOE's estimate also did not include the costs associated with fabricating SNF canisters of the correct size for waste disposal, the cost of consolidated interim storage, or the costs associated with repackaging the ever-growing inventory of SNF that is stored in canisters designed for storage and transportation, but not disposal. To put the recent DOE estimate into perspective, a 2008 cost estimate for the Yucca Mountain repository was $96.2 billion for disposal of only 70,000 MTU of SNF and HLW in a single repository – higher than the recent DOE cost estimate for disposal of 140,000 MTU of SNF. In December 2013, DOE sent a proposal to the U.S. Congress to adjust the NWF fee to zero, from the current one mill per kilowatt-hour. DOE's proposed fee adjustment was mandated in November 2013 by the D.C. Circuit following litigation against the DOE by the National Association of Regulatory Utility Commissioners. At the same time, DOE also filed a motion for rehearing of the decision by the full D.C. Circuit.

As noted previously, under the NWPA, the capacity of the first repository is limited to 70,000 MTU, of which civilian SNF would have a 60,000 MTU share with the additional 10,000 MTU of capacity being devoted to disposal of SNF and HLW from defense programs. Due to the large quantity of SNF and HLW anticipated to be disposed of in the U.S. (140,000 MTU of civilian SNF plus an additional 10,000 MTU of defense-related SNF and HLW), it is likely, therefore, that more than one repository will be necessary. After more than 30 years since passage of the NWPA that authorized DOE to develop geologic disposal capacity, the U.S. is back to the starting line and it could be many decades before a first repository is developed, let alone a second repository to dispose of the entire 140,000 MTU inventory of SNF. The daunting task of siting and operating two repositories may help to shift the U.S. focus to technologies that will reduce the quantities of commercial waste requiring disposal as well as reducing the toxicity and heat load of the waste. Pyroprocessing of SNF and subsequent recycle as metal fuel for IFRs could accomplish this as discussed in more detail below.

3.4 Summary of Once-Through Fuel Cycle and Electric Generation Costs

The SMAFS model was designed to calculate equilibrium fuel cycle costs and total electric generation costs assuming that all reactors in a given fuel cycle scheme operate at constant power and that all mass flows have reached an equilibrium. Assuming the NV unit costs identified in Appendix A for all input parameters, waste management costs, total fuel cycle costs (of which waste management costs are a subset), and total electric generation costs, expressed as the cost of electricity in mills/kWhe, are summarized in Table 3 for the OT Cycle.

Assuming the NV unit costs, the OT Cycle has reactor costs of 97.5 mills/kWhe and fuel cycle costs of 7.5 mills/kWhe, for a total cost of electricity of 105 mills/kWhe. The reactor cost comprises more than 90% of the cost of electricity.

Table 3 Total Electricity Generation Costs for the OT Cycle Assuming NV Unit Costs (Mills/kWhe)

Cost Indicators	Cost Components	Percent of Total Costs
Reactor Capital & O&M Cost	97.5	92.9%
Fuel Cycle Cost		
Natural Uranium	3.2	3.0%
Conversion	0.3	0.2%
Enrichment	1.9	1.8%
Fuel Fabrication	0.7	0.7%
Waste Management	1.4	1.3%
Total Fuel Cycle Cost	**7.5**	**7.1%**
Total Generation Cost	105.0	

The SMAFS model also includes LB and UB values for all unit costs used to calculate the equilibrium generation costs for the various fuel cycles. Table 4 summarizes the results for the OT Cycle, assuming that all unit costs are either at the LB or UB values.

Assuming the LB values for all unit costs, the OT Cycle was evaluated to have a total cost of electricity of 62.1 mills/kWhe – comprised of a reactor cost of 57.3 mills/kWhe and fuel cycle costs of 4.8 mills/kWhe. Reactor costs are more than 92% of the total cost of electric generation using the LB unit costs. Assuming the UB values for all unit costs, the OT Cycle was evaluated to have a total cost of electricity of 155.3 mills/kWhe – comprised of a reactor cost of 140.4 mills/kWhe and fuel cycle costs of 14.9 mills/kWhe. Using the UB values, reactor costs comprise approximately 90% of the total cost of generation.

Table 4 Total Electricity Generation Costs for the OT Cycle Assuming NV Unit Costs (Mills/kWhe)

Cost Indicators	LB Values	UB Values
Reactor Capital & O&M Cost	57.3	140.4
Front-End Fuel Cycle Cost	3.9	12.0
Waste Management Costs	0.9	2.9
Total Fuel Cycle Cost	**4.8**	**14.9**
Total Generation Cost	**62.1**	**155.3**

4. FAST REACTOR FUEL CYCLE WITH PYROPROCESSING

The **FR Cycle** model used for this Report assumes that UO_2 SNF from 1,450-MWe PWRs (simulating U.S. commercial LWRs) and the metal fuel from 600-MWe IFR is processed using pyroprocessing and the Pu and minor actinides are recycled into new IFR metal fuel. In addition, UO_2 SNF from the existing inventory of commercially-generated UO_2 SNF can also be processed using pyroprocessing and the Pu and minor actinides can be recycled and combined with the Pu and minor actinides from recycled IFR fuel into new IFR metal fuel. The FR Cycle modeled for this Report postulates that 63% of the energy for this fuel cycle comes from PWRs using UO_2 fuel, and 37% of the energy comes from FRs using metallic FR fuel, as shown in Figure 2. The FR Cycle assumes that the SNF inventory from existing LWRs is recycled in FRs, resulting in uranium savings of 37% (equal to the fraction of energy produced by the FRs) compared to the OT Cycle generating the same amount of energy with only LWRs. There is no direct disposal of SNF in this fuel cycle scheme. Instead, plutonium and minor actinides from UO_2 SNF, along with stored DU, are recycled for use as metal IFR fuel. In addition, plutonium and minor actinides from the IFR SNF are also recycled as metal FR fuel. FPs from UO_2 and IFR SNF, along with residual heavy metal ("HM"), are disposed in a geologic repository. The quantities of uranium fuel, plutonium, minor actinides, DU, U_{irr} and waste shown in Figure 2 are those associated with production of 1 TWhe of electricity using the FR Cycle for the recycle of UO_2 and IFR SNF. Although Figure 2 assumes the use of DU as part of the IFR fuel, U_{irr} can also be recycled in IFR metal fuel along with the Pu and minor actinides. U_{irr} can also be stored and be recycled into UO_2 fuel in the future.

It should be noted that NEA 2006 did not include a scenario in which UO_2 SNF is recycled using pyroprocessing; therefore, the data used for this report employed the waste parameters in NEA 2006 associated with reprocessing using a UREX process. The resulting parameters for FP, minor actinides, plutonium, and reprocessed uranium utilized in this study are consistent with values for pyroprocessing of UO_2 SNF that are contained in recent studies, such as a 2012 study conducted by researchers from KAERI[16] and a 2010 study by multiple authors that examined the economic and business case for pyroprocessing of UO_2 SNF.[17] Material balances for the FR Cycle are discussed in more detail later in the section.

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16 Gao, Fanxing and Won Il Ko, Korea Atomic Energy Research Institute, Economic Analysis of Different Nuclear Fuel Cycle Options, Science and Technology of Nuclear Installations, Hindawi Publishing Corporation, Volume 2012, Article ID 293467.

17 Archambeau, Charles, Blees, Change, Hunter, Shuster, Ware and Wooley, Economic/Business Case for the Pyroprocessing of Spent Nuclear Fuel ("SNF"), 100 Ton/Yr Pyroprocessing Demonstration Plant, November 2010.

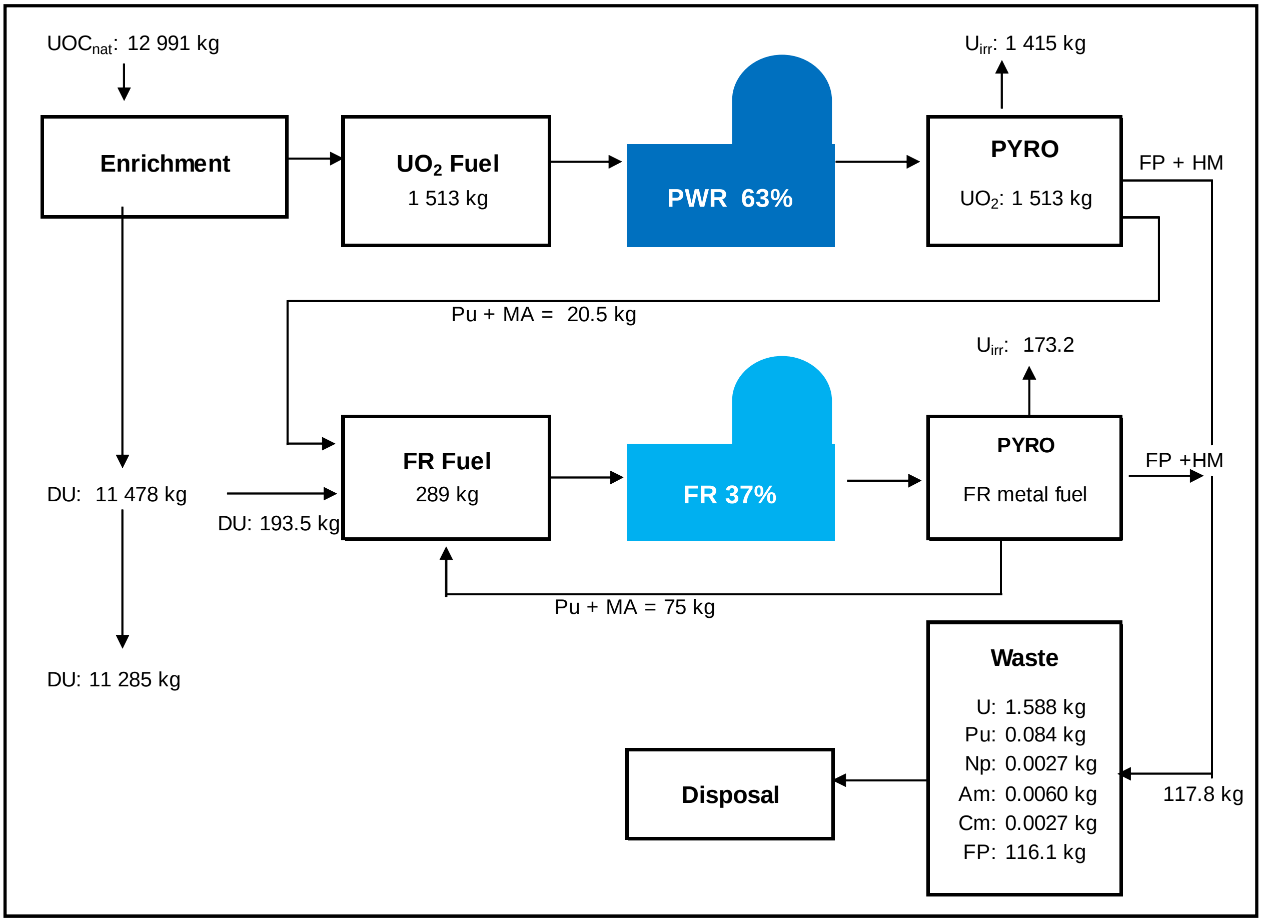

Figure 2 Fast Reactor Fuel Cycle: UO2 and IFR Fuel Pyroprocessing [18]

4.1 Overview of Integral Fast Reactors and Pyroprocessing Development

FR technology has been demonstrated on a small scale for decades and continues to be developed on larger scales in several countries. FRs were first developed in the U.S. in the 1940s with the development of the Clementine FR at Los Alamos National Laboratory and the Experimental Breeder Reactor ("EBR-I" and "EBR II") at the Idaho National Laboratory ("INL") in the 1950s and 1960s. Fermi 1 in Michigan was a prototype fast breeder reactor ("FBR") that was closed in the 1970s, and the Fast Flux Test Facility operated from 1982 to 1992 at Hanford Washington. In the U.S., Argonne National Laboratory ("ANL") developed the IFR technology (originally called the Advanced Liquid-Metal Reactor) in the 1980s. General Electric's PRISM reactor design is based on the IFR design. The PRISM reactor is an advanced fast neutron reactor that is designed to consume

18 Figure 2 assumes that DU is recycled as part of the IFR metal fuel along with Pu and minor actinides from UO_2 SNF and IFR SNF. However, Uirr can also be recycled in IFR metal fuel along with the Pu and minor actinides as assumed in several IFR concepts that are under development today. Uirr can also be stored for future recycle into UO_2 fuel.

the Pu and minor actinides (rather than disposing of them in SNF) as it generates electricity.[19]

There are currently several FRs in operation around the globe. Russia's BN-600, which is scheduled to cease operation in 2014 and the recently commissioned BN-800 reactor, which is expected to enter commercial operation in 2015, are both liquid metal FBRs ("LMFBR"). In Japan, the Monju LMFBR, operated by the Japan Atomic Energy Agency, was commissioned in 1994, but is currently not operating. India has a FR under construction at Kalpakkam. France operated the Phenix and Superphenix FRs - both units have ceased operation.

For the FR Cycle, the UO_2 SNF would be transported to the pyroprocessing facility where the Pu, minor actinides, FPs, and U_{irr} would be separated as shown in Figure 2. Pyroprocessing utilizes a high-temperature electrorefining process to separate the constituent materials in UO_2 SNF. While there are different variations for pyroprocessing, the process developed by ANL for the IFR program is described briefly below.[20] Research into pyroprocessing techniques is being conducted in the U.S. as part of DOE's Fuel Cycle Research and Development program, and in South Korea by KAERI, which is working to develop a closed fuel cycle that includes pyroprocessing and FRs using metallic fuel.[21] It should be noted that in pyroprocessing, no pure plutonium stream is separated during SNF processing. Instead, the plutonium remains combined with the minor actinides throughout the process. This results in the plutonium being more proliferation resistant than the pure plutonium steam that results from aqueous reprocessing (the type of reprocessing currently used in Europe), in which the minor actinides remain with the FPs and are disposed as part of the HLW.

In order for UO_2 SNF to be partitioned through pyroprocessing, it first must go through an oxide reduction step in order to convert it to a metallic form. The SNF is chopped into segments, loaded into anode baskets and the baskets are lowered into the electrorefiner. The electrorefiner performs the primary separation of the actinides from the FPs. In order to partition the constituent elements in metallic FR SNF, it is not necessary to subject IFR SNF to an oxide reduction step since the fuel is already in metallic form. The remaining processes for separation of the actinides and FPs are the same as for UO_2 SNF.[22]

19 Fletcher, Kelly, Sustainable Energy Advanced Technology Leader, General Electric Company, Prepared Testimony before the Energy and Water Subcommittee , U.S. Senate Appropriations Committee, September 14, 2006.

20 Simpson, Michael F., Jack D. Law, Idaho National Laboratory, *Nuclear Fuel Reprocessing*, INL/EXT-10-1753, February 2010.

21 Ibid.

22 Ibid.

4.2 FR Cycle Material Balance

The front-end of the portion of the FR Cycle that uses the reference PWR is identical to the front-end of the OT Cycle. As in the OT Cycle, the production of UO_2 fuel for the reference PWR includes uranium mining and milling, conversion and enrichment services and fuel fabrication as previously described in Section 3.1. However, in the FR Cycle, the reference PWR contributes only 63% of 1 TWhe of electricity generated.

The resulting separation products from pyroprocessing 1,513 kg of UO_2 SNF from the reference PWR is summarized in Table 5: 1415 kg of U_{irr}, 20.5 kg Pu and minor actinides, and 77 kg of FPs including traces of uranium and other elements in the FP waste stream.[23] Plutonium plus minor actinides are recycled into FR metal fuel as previously shown in Figure 2.

The resulting separation products from pyroprocessing 289 kg of metallic FR SNF are summarized in Table 5: 173.2 kg of U_{irr}, 75 kg of Pu and minor actinides, and 40.3 kg of FPs. In total, 95.5 kg of Pu and minor actinides are recycled in the equilibrium FR shown in Figure 2 along with 193.5 kg of DU (or U_{irr}). Total FPs requiring disposal in the FR Cycle are an estimated 118 kg.

Table 5
Composition of UO_2 and FR SNF Resulting per TWhe

SNF Constituents	UO_2 SNF (kg)	FR Metal SNF (kg)	Total SNF Constituents (kg)
Irradiated uranium	1415	173.2	1588
Plutonium	18.2	66.0	84.2
Minor Actinides	2.3	9.0	11.3
Fission Products, plus trace quantities of HM	77.4	40.3	117.7
Total	1513	289	1802

Note: Numbers may not add exactly due to rounding.

23 Simpson, Michael F., Jack D. Law, Idaho National Laboratory, Nuclear Fuel Reprocessing, INL/EXT-10-1753, February 2010. The various waste streams may be treated using different processes – FPs can be processed into a HLW ceramic waste form, while SNF cladding and noble metals can be processed in a metal waste furnace into a HLW metal form.

4.3 Recycling SNF

As noted in Section 1, through December 2013, an estimated 72,000 MTU of UO_2 SNF had been discharged from U.S. NPPs and was in storage at NPP sites in the U.S, an amount that is already in excess of the NWPA's statutory capacity of 70,000 MTU for a first repository. By 2040, an estimated 127,000 MTU of SNF will have been discharged, growing to an estimated 140,000 by 2070.

As previously shown in Figure 2, the FR generates 37% of the electricity necessary to produce 1 TWhe in the FR Cycle. This represents an estimated 47 MWe and the PWR portion of electricity represents an estimated 80 MWe. The 47 MWe represented by FR generation in the FR Cycle requires metallic FR fuel containing 0.095 MT of Pu and minor actinides plus an additional 0.194 MT of DU. To refuel a 600 MWe IFR, an estimated 1.2 MT of Pu and minor actinides, and 2.5 MT of DU are necessary, as shown in Table 6. It is envisioned that IFRs will be deployed in multiple units at one site. To refuel two 600 MWe IFRs (1,200 MWe total), 2.4 MT of Pu and minor actinides, and 5.0 MT of DU are needed.

Table 6 Estimate of Pu and Minor Actinides and DU to Supply Metallic FR Fuel

Reload Fuel Component	47 MWe	600 MWe	1200 MWe
Pu & MA (MT)	0.095	1.2	2.4
Depleted Uranium (MT)	0.194	2.5	5.0
Total Fuel (MT)	0.29	3.7	7.4

As was shown in Table 1, the constituent elements in UO_2 SNF include an estimated 1.5% of Pu and minor actinides. Thus, in order to separate 2.4 MT of Pu and minor actinides needed to refuel two 600 MWe FRs (1,200 MWE total), 160 MTU of UO_2 SNF would need to be pyroprocessed (2.4 MT / 0.015). Table 7 summarizes the estimated inventory of Pu and minor actinides that is contained in current and projected inventories of UO_2 SNF. Hypothetically, if the reload fuel for two 600 MWe FRs consumes 2.4 MT of Pu and minor actinides from processing 160 MTU of UO_2 SNF, then the current inventory of 72,000 MTU of UO_2 SNF, consumed at a rate of 160 MTU per FR per year, would require an estimated 22,600 MWe IFRs (or 11 sites, each with 2 IFRs) to consume the current inventory of Pu and minor actinides contained in UO_2 SNF.[24] In order to consume the Pu

24 An estimated 11 Fast Reactor Sites is derived from dividing the current inventory of 72,000 MTU of UO_2 SNF by 160 MTU consumed per 1,200 MWE per year, assuming 40 years of FR operation, assuming 2,600 MWE FRs ([72,000 ÷ 160 ÷ 40] * 2 = 22)

and minor actinides from 127,000 MTU of UO_2 SNF, a fleet of 40 600 MWe IFRs operating for 40 years would be necessary.

Table 7 Estimate of Pu and Minor Actinides, U_{irr} and FP Produced in Current and Projected UO_2 Inventory (MT)

Constituents of UO_2 SNF	2013	2020	2040
Quantity of UO_2 SNF	72,000	86,700	127,000
Irradiated Uranium – 93%	66,960	80,631	118,110
Pu + Minor Actinides – 1.5%	1,080	1,300	1,905
Fission Products – 5.5%	3,960	4,769	6,985
DU (or U_{irr}) Consumed Over 40 years (MTU)	2,200	2,700	4,000
# 600 MWe FRs, Operating 40 Years	22	27	40

As shown in Table 6, 2.5 MT of DU is needed to fuel a 600 MWe IFR each year. Therefore, over a 40-year period, a 600 MWe IFR will consume 100 MT of DU. As shown in Table 7, the 22 IFRs needed to recycle the existing 72,000 MT of UO_2 SNF, would consume 2,200 MTU of DU (or alternatively U_{irr}) and 40 IFRs needed to recycle 127,000 MTU that will exist by 2040 will consume 4,000 MTU of DU. There are 686,500 MTU of DU in storage at three former gaseous diffusion enrichment plants in Kentucky, Ohio and Tennessee.[25] While DU with higher uranium tails assay can be re-enriched to create natural uranium equivalent, significant quantities of DU will require continued storage and eventual disposal unless this material can be recycled. Alternatively, U_{irr} may also be recycled instead of DU.

It should also be noted that while two 600 MWe IFRs (1,200 MWe total) are consuming Pu and minor actinides from UO_2 SNF, the IFRs are also producing additional Pu and minor actinides as summarized in Table 8. Two 600 MWe IFRs (1,200 MWe total) will produce an additional 1.9 MT of Pu and minor actinides, while consuming 2.4 MT of Pu and minor actinides. This is a net reduction of 0.5 MT of Pu and minor actinide elements for each year of IFR operation. The estimated number of IFRs needed to consume inventories of Pu and minor actinides from the current inventory of UO_2 SNF shown in Table 7 does not include the further recycle of IFR SNF as a fuel source for continued operation of this IFR fleet. This is because the focus of this report is on the use of pyroprocessing and IFRs to recycle the current inventory of commercial UO_2 SNF. However, the recycle of Pu and minor actinides from IFR SNF would provide a fuel for IFRs going forward once existing

25 Depleted UF6 Management Information Network, http://web.ead.anl.gov/uranium/faq/storage/faq16.cfm

inventories of LWR SNF are consumed. The Pu and minor actinides recycled from IFR SNF also could be combined with Pu and minor actinides recycled from existing UO_2 SNF. However, this would result in either (1) a longer time period to recycle existing UO_2 inventories in the IFR fleets identified in Table 7 or (2) construction of a larger number of IFRs to consume Pu and minor actinides from both UO_2 inventories and IFR SNF processing. Whether Pu and minor actinides from IFR SNF are recycled along with UO_2 SNF or recycled at a later date into additional IFR metal fuel, the Pu would not be separated from the minor actinides, providing proliferation resistance and reducing concerns regarding proliferation.

Table 8 Estimate of Pu and Minor Actinides, U_{irr} and FP Produced in IFR Fuel (MT)

Reload Fuel Component	47 MWe	600 MWe (1 IFR)	1200 MWe (2 IFRs)
Quantity of FR SNF	0.289	3.7	7.4
Irradiated Uranium – 60%	0.173	2.2	4.4
Pu + Minor Actinides – 26%	0.075	0.96	1.9
Fission Products – 14%	0.040	0.5	1.0

4.4 Waste Volumes for FR Cycle

The SMAFS model includes assumptions regarding volumes of LILW, HLW, and SNF produced during the front end of the nuclear fuel cycle, during reactor operations, and as a result of reprocessing operations. Under a FR Cycle, a total volume of 11.9 m^3/TWhe of LILW-SL is produced including waste from the front-end of the fuel cycle and from reactor operation and a volume of 2.3 m^3/TWhe of LILW-LL is produced, as shown in Table 9. The volume of HLW requiring disposal is estimated to be 0.4 $m^{3.}$ The volume of earthen material that must be excavated to dispose of SNF for a given repository design, is based on the decay heat load of the HLW, as discussed in more detail in Appendix A. Since the Pu and minor actinides have been removed from the constituent elements of the HLW, the overall decay heat of the HLW waste is lower than for direct disposal of SNF, reducing the amount of earth that would have to be excavated to dispose of HLW from pyroprocessing of UO_2 SNF compared to direct disposal. To dispose of the 0.4 m^3 of HLW, 38.3 m^3 of earth would have to be excavated, based on the decay heat (kW) of the SNF.

Table 9 Key Waste Parameters Associated with the FR Cycle

Waste Parameter	Volume
LILW-SL	11.9
LILW-LL	2.3
HLW	0.4
SNF	0
HLW Repository Excavation	38.3

In addition to the above LILW, HLW, SNF and disposal excavation volume, 11,478 kg DU require storage or can be recycled in metallic FR fuel.

4.5 Pyroprocessing Plant Financing

In order to close the nuclear fuel cycle in the U.S., it will be necessary to construct and operate facilities for recycling of SNF; both recycling of UO_2 SNF from PWRs and recycling of metallic IFR SNF. A summary of a cost analysis conducted by ERI for a 2,000 MTHM per year pyroprocessing plant is provided below, including the results of a sensitivity analysis of financial parameters concerning construction and operation of this plant. Initial cost parameters used in the base case analysis are based on a November 2010 study performed by multiple individuals regarding the development of a 100 MTHM pyroprocessing *demonstration* facility in the U.S. ("2010 Archambeau study.")[26] The 2010 Archambeau study also examined the costs associated with development of a 2,000 MTHM pyroprocessing facility. Sensitivity analyses performed by ERI examine a range of debt positions, return on investment, debt interest rates, financing periods, and total overnight costs.

The financial assumptions and operating parameters utilized in the 2010 Archambeau study were used to form the base case assumptions in ERI's analysis of the financing alternatives for a 2,000 MTHM pyroprocessing plant, as summarized in Table 10. ERI developed a MSExcel spreadsheet to calculate the unit costs for a base case analysis that models a pyroprocessing plant with a 2,000-ton capacity for processing UO_2 SNF from the current U.S. nuclear power plants, partitioning U_{irr}, Pu, minor actinides, and FPs, and future

26 Archambeau, Charles, Blees, Chang, Hunter, Shuster, Ware and Wooley, Economic/Business Case for the Pyroprocessing of Spent Nuclear Fuel (SNF), 100 Ton/Yr Pyroprocessing Demonstration Plant, November 2010

recycling of Pu and minor actinides in an IFR.[27] The facility is assumed to operate for a period of 25 years. Initial overnight capital costs are assumed to be $7 billion with annual O&M costs of $500/kgHM processed. A depreciation period of 25 years is assumed. The ratio of debt to equity is 60:40, with a debt interest rate of 6% and a loan payback period of 15 years. ERI utilized its own assumptions for the return on investment ("ROI") of 15% and a Federal corporate income tax rate of 35%, as these factors were not explicitly identified in the 2010 Archambeau study.

The levelized reprocessing unit cost that results from the base case assumptions shown in Table 10 is an estimated $1,218/kgHM reprocessed in the plant. In an addendum to the 2010 Archambeau study, a $1,200 processing fee for UO_2 SNF was assumed, which is the same order of magnitude as the unit cost calculated by ERI.

Table 10 2,000 MTHM Pyroprocessing Plant Financial and Operating Assumptions

Base Case Parameters	Base Case Assumptions
Plant Capacity	2,000 MTHM/year
Operating Period	25 years
Overnight Cost	$7 Billion
Operating and Maintenance Cost	$500/kgHM
Debt Ratio	60%
Debt Interest Rate	6%
Equity Ratio	40%
Return on Investment	15%
Federal Taxes	35%
Depreciation Period	25 years
Loan Payback Period	15 years

In addition to calculating unit costs for a pyroprocessing plant using the above base case assumptions, ERI performed sensitivity analyses to determine the impact of changes to the financial and operating assumptions. As summarized in Table 11, values that are ±50% of the capital cost, and ±25% of the other parameters were varied one-at-a-time in order to determine the sensitivity of the unit cost of pyroprocessing at a 2,000-ton pyroprocessing plant to changes in the various parameters.

27 While Pu and minor actinides are recycled in FRs and FPs are disposed of as HLW, the U_{irr} is assumed to be stored for future recycle as UO_2 fuel for LWRs. U_{irr} from aqueous reprocessing in Europe has been recycled as LWR fuel in European reactors.

Table 11 Sensitivity Analysis Parameters for Financial and Operating Assumptions

	Lower Bound Sensitivity	Upper Bound Sensitivity
Plant Capacity (MTHM/year)	2,000	2,000
Overnight Cost	$10.5 Billion	$3.5 Billion
Operating and Maintenance Cost	$375/kgHM	$625/kgHM
Debt Ratio	45%	75%
Loan Payback Period	11.25 years	18.75 years
Debt Interest Rate	4.5%	7.5%
Equity Ratio	55%	25%
Return on Investment	11.25%	18.75%
Federal Taxes	35%	

By varying the above financial parameters one-at-a-time, ERI was able to determine which of the financial parameters have the greatest impact on the cost of pyroprocessing per MTHM processed. Figure 3 summarizes the results of the sensitivity analysis using the lower bound and upper bound parameters identified in Table 11 and compares the results to the base case unit cost of $1,218/kgHM for pyroprocessing of UO_2 SNF at the 2,000-ton facility.

- The base case overnight capital cost of $7 billion was varied from $3.5 billion to $10.5 billion, resulting in unit costs of $860 to $1,579 per kgHM, respectively.
- Annual O&M costs were varied from $375/kgHM to $625/kgHM, resulting in unit costs of $1,091 to $1,345 per kgHM, respectively.
- The ROI was varied from 11.25% to 18.75%, resulting in unit costs of $1,060 to $1,395 per kgHM.
- Debt ratio was varied from 45% to 75%, resulting in unit costs of $1,299 to $1,139 per kgHM, respectively.
- The debt rate was varied separately from 4.5% to 7.5%, resulting in unit costs of $1,188 to $1,253 per kgHM, respectively.
- The loan repayment period was varied from 11.25 years to 18.75 years resulting in unit costs of $1,264/kgHM to $1,181/kgHM, respectively.

The overnight capital cost of a pyroprocessing plant will have the greatest impact on the unit costs for pyroprocessing UO_2 SNF, as shown in Figure 3. Other financial parameters that will be important to the unit costs for a pyroprocessing plant are the required ROI, the annual O&M costs, and the ratio of debt to equity.

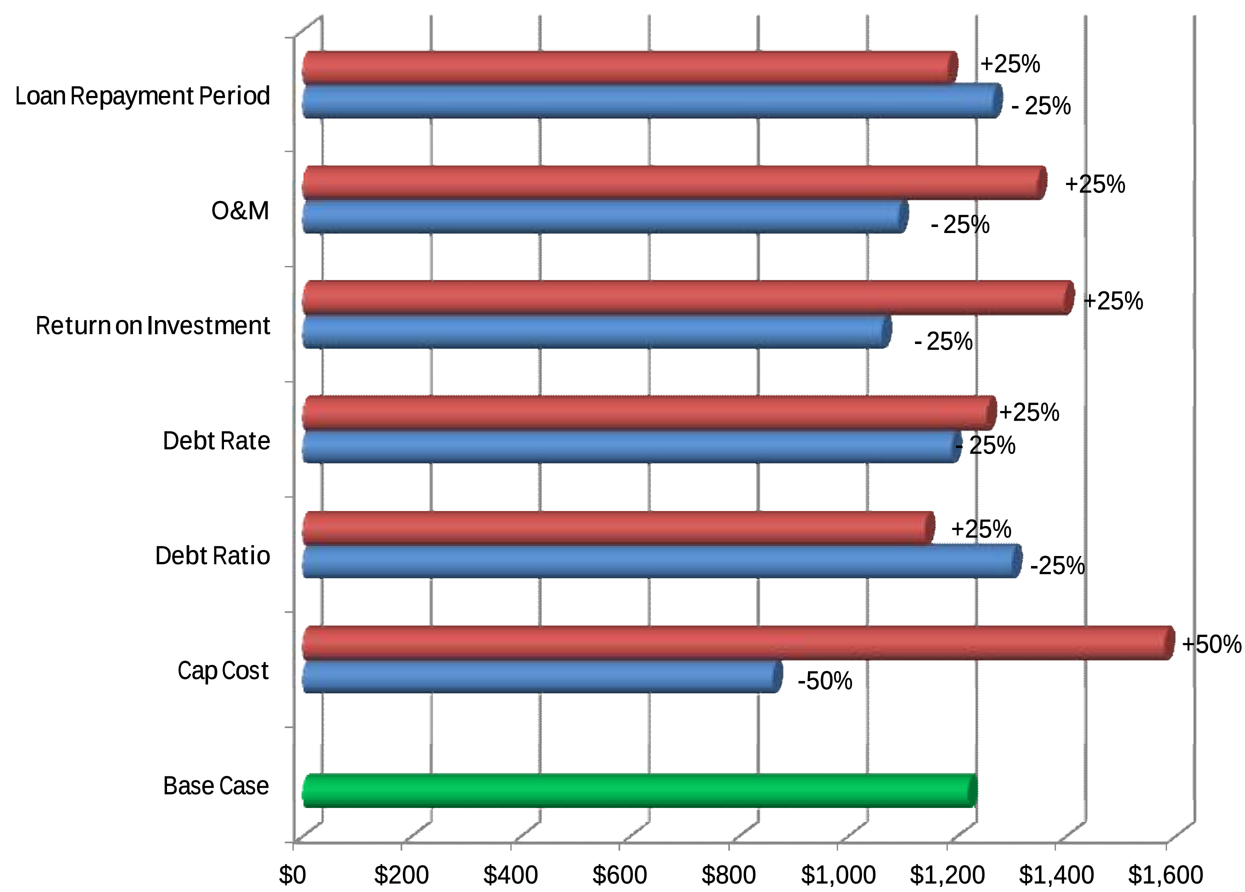

Figure 3 Comparison of Unit Costs for Pyroprocessing of UO_2 SNF In a 2,000-Ton Plant Over a Range of Financial Parameters

4.6 Summary of FR Cycle and Electric Generation Costs

The SMAFS model was designed to calculate equilibrium fuel cycle costs and total electric generation costs assuming that all reactors in a given fuel cycle scheme operate at constant power and that all mass flows have reached an equilibrium. Assuming the NV unit costs identified in Appendix A for all input parameters, waste management costs, total fuel cycle costs (of which waste management costs are subset), and total electric generation costs, expressed as the cost of electricity in mills/kWhe, are summarized in Table 12 for the FR Cycle.

Assuming the NV unit costs, the FR Cycle, in which UO_2 SNF from operating PWRs is pyroprocessed along with IFR SNF to provide feed for IFR metal fuel, has equilibrium reactor costs of 96.2 mills/kWhe and fuel cycle costs of 7.8 mills/kWhe, for a total cost of electricity of 104 mills/kWhe. The reactor cost comprises an estimated 93% of the cost of electricity.

Table 12 Total Electricity Generation Costs for the FR Cycle Assuming NV Unit Costs (Mills/kWhe)

Cost Indicators	Cost Components	Percent of Total Costs
Reactor Capital & O&M Cost	**96.2**	**93%**
Fuel Cycle Cost		
Natural Uranium	2.0	2%
Conversion	0.2	0%
Enrichment	1.1	1%
Fuel Fabrication	1.3	1%
UO_2 & IFR Reprocessing	2.9	3%
Waste Management	0.3	0%
Total Fuel Cycle Cost	**7.8**	**7%**
Total Generation Cost	**104**	**100%**

The SMAFS model also includes LB and UB values for all unit costs utilized to calculate the equilibrium generation costs for the various fuel cycles. Table 13 summarizes the results for the FR Cycle, assuming that all unit costs are either at the LB or UB values. Assuming the LB values for all unit costs, the FR Cycle was evaluated to have a total cost of electricity of 54.7 mills/kWhe, with a reactor cost of 50.2 mills/kWhe and fuel cycle costs of 4.5 mills/kWhe. Reactor costs are more than 91% of the total cost of electric generation using the LB unit costs. Assuming the UB values for all unit costs, the FR Cycle was evaluated to have a total cost of electricity of 151.5 mills/kWhe, with a reactor cost of 136.4 mills/kWhe and fuel cycle costs of 15.1 mills/kWhe. Using the UB values, reactor costs comprise 90% of the total cost of generation.

Table 13 Total Electricity Generation Costs for the FR Cycle Assuming NV Unit Costs (Mills/kWhe)

Cost Indicators	LB Values	UB Values
Reactor Capital & O&M Cost	50.2	136.4
Front-End Fuel Cycle Cost	2.9	9.0
UO_2 & IFR Reprocessing	1.4	5.2
Waste Management Costs	0.2	0.9
Total Fuel Cycle Cost	**4.5**	**15.1**
Total Generation Cost	**54.7**	**151.5**

5. COMPARISON OF WASTE VOLUME, RADIOTOXICITY AND THERMAL OUTPUT FOR OT CYCLE AND FR CYCLE

Table 14 compares the volumes of LILW, HLW, and SNF produced during the front end of the nuclear fuel cycle, reactor operations, and as a result of reprocessing operations for the OT Cycle and FR Cycle. Under the OT Cycle, a total volume of 14.7 m^3/TWhe of LILW-SL (including waste from the front-end of the fuel cycle and during reactor operation) and 0.3 m^3/TWhe of LILW-LL are produced. Under the FR Cycle, LILW-SL volumes are lower than in the OT Cycle – 11.9 m^3/TWhe of LILW-SL. However, LILW-SL volumes are higher in the FR Cycle – 2.3 m^3/TWhe. The volume of SNF in the OT Cycle requiring direct disposal is estimated to be 1.5 m^3/TWhe compared to 0.4 m^3/TWhe of HLW for the FR Cycle.

Disposal costs will be a function not only of the volume of waste being disposed but also of the heat load of the waste requiring disposal. This is due to the fact that repository designs typically assume that a certain amount of repository space is needed for SNF/HLW of a specific heat load in order to have a uniform heat load throughout the repository. SNF/HLW with lower heat loads per unit volume of waste can be emplaced at closer distances than waste with higher heat loads. In the SMAFS model, this is accounted for with the SNF Repository Excavation parameter as shown in Table 14. Disposal of SNF in the OT Cycle requires 86.5 m^3/kW of waste disposed. Disposal of HLW resulting from the FR Cycle requires 38.3 m^3/kW of waste disposed, less than half of the repository volume required to disposal of SNF in the OT Cycle

Table 14 Comparison of Waste-Related Volumes Produced in the OT Cycle and FR Cycle

Waste-Related Parameter	OT Cycle Waste Volume	FR Cycle Waste Volumes
LILW-SL (m^3/TWhe)	14.7	11.9
LILW-LL (m^3/TWhe)	0.3	2.3
HLW (m^3/TWhe)	0	0.4
SNF (m^3/TWhe)	1.5	0
SNF Repository Excavation (m^3/kW)	86.5	38.3

Table 15 compares the radioactivity and thermal output of waste volumes for the OT and FR Cycles in Terabecquerel/TWhe ("TBq/TWhe") at time periods of 200 years after discharge from the NPP and 1,000 years after discharge. UO_2 SNF from the OT Cycle has an activity of 1,070 TBq/TWhe at 200 years and this is reduced to 201 TBq/TWhe at the 1,000 year mark – 18% of the original activity. The HLW volumes from the FR Cycle (387 TBq/TWhe) at 200 years are only 36% of those for the OT Cycle and at 1,000 years (2.4 TBq/TWhe) are 1% of the activity for the OT Cycle. Similarly, the heat load of the waste to be disposed decreases significantly in the FR Cycle. At 200 years, the OT Cycle waste has a heat load of 591 watts/TWhe compared to 30 watts/TWhe for the FR Cycle, 5% of the OT Cycle heat load. At 1,000 years, the FR Cycle waste heat load (0.5 watts/TWhe) are <1% of the OT Cycle heat load (171 watts/TWhe).

Table 15 Comparison of Radiotoxicity and Thermal Output of Waste Produced in the OT Cycle and FR Cycle (m3/TWhe)

	OT Cycle Waste Parameters	FR Cycle
Activity – 200 years (TBq/TWhe)	1,070	387
Activity – 1,000 years (TBq/TWhe)	201	2.4
Thermal Output – 200 Years (Watts/TWhe)	591	30
Thermal Output –1,000 Years (Watts/TWhe)	171	0.5

As shown in Table 15, pyroprocessing of UO_2 SNF for recycle of Pu and minor actinides in metallic FR fuel removes the majority of the long-lived isotopes from the waste stream and reduces long-term radioactivity or radiotoxicity. Developing a repository for disposal of commercial waste with a lower radiotoxicity and without the long-lived isotopes should result in simplified repository design, including avoidance of the need for some engineering barriers, ultimately reducing cost. As an example, the Yucca Mountain repository project was designed with a complex engineered barrier system that utilizes drip shields made of titanium (an expensive metal) and specialty metals in the waste disposal package in order to protect the waste packages from corrosion for thousands of years after emplacement. The cost to fabricate and install the drip shields was estimated to cost several billion dollars - costs that would not be necessary for disposal of wastes with lower activity and without the inventory of long-lived radioisotopes.

The thermal load of the FR Cycle waste is also significantly lower than the waste for the OT Cycle – 0.5 watts/TWhe for the FR Cycle compared to 171 watts/TWhe for the OT Cycle – less than 1% of the heat load of OT Cycle waste at 1,000 years. As noted above, the distance between each disposal canister and between rows of disposal canisters in a geologic repository can be reduced if the heat load of the emplaced waste is reduced due to the fact that repository designs typically assume that a certain amount of repository space is needed for disposal of a SNF/HLW with a specific thermal output. Therefore, the size of the required repository excavation is a function of the heat load of the waste being emplaced. Accordingly, a significant reduction in heat load will also reduce the cost of repository development since less material will have to be excavated. The repository size needed to dispose of the HLW that results from pyroprocessing existing inventories of UO_2 SNF could be halved compared to that needed to directly dispose of UO_2 SNF – that is, there would not be the need for a second repository to be constructed in the U.S.

6. CONCLUSIONS

Deploying "pyroprocessing" technology and IFRs to recycle the current inventory of commercial UO_2 SNF provides a number of significant, potential benefits, key among these are: avoiding the need for additional costs associated with a second repository by reducing the overall volume of radioactive waste requiring geologic disposal; reducing the radiotoxicity and heat load of the final waste form to be disposed, which would reduce the cost of the design and construction of the single geologic repository needed for nuclear waste; and the ability to pay for pyroprocessing/IFR costs by the avoided cost of a second repository. In addition, if a large-scale pyroprocessing facility and a fleet of IFRs are able to be deployed sooner than a geologic repository, then there also may be avoided costs associated with the government's liability for the DOE's failure to begin SNF acceptance in 1998. Deployment of pyroprocessing and IFRs also will help to conserve uranium resources, thereby prolonging the use of nuclear energy if uranium supplies become scarce or the price of uranium increases significantly.

6.1 Reduction in Waste Volume, Radiotoxicity, and Heat Load of Waste Requiring Disposal

Assuming the NWPA statutory capacity for a first repository of 70,000 MTU of SNF, the projected 140,000 inventory of commercial UO_2 SNF, plus an estimated 10,000 MTU of SNF and HLW from U.S. defense programs, would require that at least two repositories be built in the U.S. As shown in Table 14, the volume of HLW resulting from the FR Cycle that requires disposal (0.4 m^3/TWhe) is 27% of the same volume of UO_2 SNF (2,050 kg) requiring disposal (1.5 m^3/TWhe) in the OT Cycle. While the entire inventory of UO_2 SNF may not be suitable for pyroprocessing and recycle of TRU elements in metallic IFR fuel, clearly, significant reductions in the volume of material to be disposed can be realized to avoid building a second repository.

In addition to the reduced volume of waste, as shown in Table 14, the HLW resulting from pyroprocessing that requires disposal in the FR Cycle has a lower radiotoxicity at 1,000 years after discharge from the reactor due to the recycle of Pu and minor actinides in FR metal fuel – FR Cycle HLW contains only 1% of the activity found in OT Cycle waste at 1000 years after discharge as summarized in Table 15. The thermal load of the FR Cycle waste is also significantly lower than the waste for the OT Cycle – it is less than 1% of the heat load of OT Cycle waste at 1,000 years. The distance between each disposal canister and between rows of disposal canisters in a geologic repository can be reduced if the heat load of the emplaced waste is reduced. This is due to the fact that repository designs typically assume that a certain amount of repository space is needed for disposal of SNF/HLW with a specific thermal output (watts/m^3). Therefore, the size of the required repository excavation is a function of the heat load of the waste being emplaced. Accordingly, a significant reduction in heat load will reduce the cost of repository development since less material will be excavated. Due to the reduction in the thermal load of HLW from the FR Cycle, as shown in Table 15, the amount of material required to be excavated to emplace that waste in a repository in the FR cycle is also reduced - from

86.5 m^3 for the OT Cycle to 38.3 m^3 for the FR Cycle. This results in 44% of the required repository volume for disposal of SNF being needed to dispose of HLW from processing UO_2 SNF, which could lead to the need to develop only one repository and substantially reduce the cost to dispose of HLW.

In addition, recycling SNF in metallic IFR fuel removes the majority of the long-lived isotopes from the waste stream and reduces long-term radioactivity or radiotoxicity. Developing a repository for disposal of commercial waste with a lower radiotoxicity and without the long-lived isotopes should result in simplified repository design, including avoidance of the need for some engineering barriers, ultimately reducing cost. As an example, the Yucca Mountain repository project was designed with a complex engineered barrier system that utilizes drip shields made of titanium (an expensive metal) and specialty metals in the waste disposal package in order to protect the waste packages from corrosion for thousands of years after emplacement. The cost to fabricate and install the drip shields was estimated to cost several billion dollars - costs that would not be necessary for disposal of wastes with lower activity and without the inventory of long-lived radioisotopes.

As discussed in Section 3.3, a recent cost estimate by DOE regarding the costs of various geologic repository alternatives ranged from $24 billion to $81 billion for disposal of 140,000 MTU of SNF. In addition, higher costs would likely be in order to fabricate disposal canisters, repackage SNF from existing dual-purpose canisters, and provide consolidated interim storage. While ERI has not performed a detailed cost analysis of these additional costs, a 2008 DOE cost estimate assumed that disposal canisters would cost an estimated $12.6 billion,[28] bringing the upper level of the cost estimate to $94 billion, a 16% increase. Repackaging and consolidated interim storage would raise the ultimate price tag even higher. To put the recent DOE estimate into perspective, a 2008 cost estimate for the Yucca Mountain repository was $96.2 billion for disposal of only 70,000 MTU of SNF and HLW in a single repository – higher than the recent DOE cost estimate for disposal of 140,000 MTU of SNF. Thus, the opportunity to develop only one repository and avoid the costs for developing, licensing, constructing, and operating a second repository could be realized by using pyroprocessing and IFRs to recycle SNF. If a second repository is avoided, then the cost savings attributed to pyroprocessing and IFRs could be $12 billion (half the lower range of the recent DOE cost estimate) to $96 billion (the 2008 estimate for a 70,000 MTU repository at Yucca Mountain), or higher.

6.2 Uncertainties in Schedule of U.S. Repository Program

As discussed in Section 3.3, many obstacles stand in the way of developing and executing a long-term strategy for disposal of SNF in the U.S. While the NRC has resumed its review of the Yucca Mountain LA , restart of the Yucca Mountain project is considered unlikely in the current political climate. If the Yucca Mountain project is not resurrected and the

28 U.S. DOE, Office of Civilian Radioactive Waste Management, Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007, DOE/RW-0591,July 2008

repository program restarted, then a complete overhaul of the U.S. waste program will require the NWPA to be amended by Congress; a search for one or more sites for disposal of SNF; and development, licensing, construction and operation of disposal facilities. Given the history of the U.S. waste program, it could be decades before a geologic repository begins operation in the U.S.

Siting, licensing and construction of fuel cycle facilities, such as a pyroprocessing facility can be accomplished under more predictable schedules than siting, licensing and construction of a permanent geologic disposal facility. During the past decade, four new uranium enrichment plants have been sited and licensed and one plant has been constructed and operated. In addition, the construction of a specialty fuel fabrication facility was authorized during the same time period. In addition, U.S. regulations for siting and licensing NPPs have been successfully used for construction of four new NPPs expected to begin operation between 2015 and 2020.

If a large-scale pyroprocessing facility can be deployed earlier than a repository and begin accepting SNF from U.S. NPP sites sooner than a geologic repository, then there may be additional avoided costs associated with continued payments to nuclear operating companies associated with DOE's failure to begin SNF acceptance in 1998 in accordance with the Standard Contract for Disposal of SNF and/or HLW. DOE has estimated that its annual liability is on the order of $0.5 billion per year – resulting in the potential for significant avoided costs for the government.

6.3 Prolonged Supply of Uranium Resources

IFRs do not consume natural uranium and therefore help to prolong the use of nuclear energy if uranium supplies become scarce or the price of uranium increases significantly.

APPENDIX A STEADY-STATE SMAFS MODEL INPUT ASSUMPTIONS

Unit costs in the SMAFS model were updated for this study in order to reflect cost assumptions that are indicative of current and expected future UO_2 fuel unit costs (uranium, enrichment, conversion and fuel fabrication), waste management costs that are indicative of U.S.-specific costs, and recent experience with costs for investment in new LWRs. Unit costs associated with the FR Cycle are based on recent published studies of FR metal fuel fabrication and UO_2 and FR pyroprocessing costs. The LB and UB unit costs for the FR Cycle reflect the current uncertainty associated with fuel cycle costs and FR capital costs for this fuel cycle.

A.1 Front-End Unit Costs

The unit costs that comprise the front-end of the nuclear fuel cycle include natural uranium ore concentrates ("UOC" or "U_3O_8"); conversion of UOC to natural uranium hexafluoride ("UF_6"), enrichment of natural UF_6 to enriched UF_6, and fabrication of uranium-oxide ("UO_2") nuclear fuel assemblies. Both fuel cycles considered in this report assume the use of PWRs that utilize UO_2 fuel as one of the steps in the fuel cycle.

A.1.1 Uranium Ore Concentrates

This study assumes the NV unit cost for natural UOC is \$60/lb U_3O_8 (\$156/kgU); a LB of \$35/lb U_3O_8 (\$90/kgU), and a UB of \$150/lb U_3O_8 (\$390/kgU). While the NEA Study assumed that the unit cost of depleted uranium was the same as the unit cost for UOC, this study assumes that depleted uranium has a value that is 50% of the unit cost for UOC since there are ample stores of depleted uranium in both government and private inventories.

A.1.2 Conversion Services

Unit costs for conversion services assume a NV of \$15/kgU as UF6, a LB of \$7/kgU as UF6, and an UB of \$20/kgU as UF6.

A.1.3 Enrichment Services

Unit costs for enrichment services assume a NV of \$120 per Separative Work Unit ("SWU"), a LB value of \$80/SWU and an UB of \$175/SWU.

A.1.4 Fuel Fabrication

The NV unit costs for UO_2 fuel fabrication are based on current market prices for PWR fuel – a NV of $320 per kilogram heavy metal ("kgHM"), a LB of $280/kgHM and an UB of $365/kgHM.

NEA 2006 assumed that FR metal fuel fabrication would have a NV of $2,600/kgHM, $1,400/kgHM for the LB, and $5,000/kgHM for the UB. A recent study from researchers at KAERI identified a single cost for pyroprocessing and FR metal fuel fabrication (NV: $5,000/kgHM, LB:$2,500/kgHM, UB: $7,500/kgHM), but did not identify the portion of these costs attributable to fabrication.[29] Since the overall values in NEA 2006 and the KAERI study for pyroprocessing and FR metal fuel fabrication are similar, the ratio between the cost for fabrication and pyroprocessing in NEA 2006 was applied to the KAERI value of $5,000/kgHM. This resulted in FR metal fuel fabrication costs of $2,900/kgHM, LB of $1,400/kgHM, and UB of $5,000/kgHM.

A.2 Reactor Investment Unit Costs

The SMAFS model includes assumptions for the unit cost of installed power and the load factors for a PWR and FR. The unit costs for a PWR assume a NV of $5,600/kWe, a LB of $4,500/kWe, and an UB of $6,500/kWe. The unit costs for a FR include a NV of 5,400/kWe, a LB of $3,000/kWe; and an UB of $6,400/kWe. The NVs for the PWR are based on recently published estimates of overnight capital costs by the U.S. Department of Energy's Energy Information Agency, escalated to 2013 dollars.[30] The NV for a FR is based on recently published reactor costs from a study by researchers from KAERI, escalated to 2013 dollars.[31]

A.3 Spent fuel pool storage onsite

The costs for interim storage of SNF include a fixed component and a component that is time dependent. For interim storage of UO_2 SNF, the fixed interim storage cost to store SNF in reactor pools (not dry storage) assumes a NV of $50/kgHM and a variable value of $5/kgHM per year stored. The LB values are $40/kgHM and $5/kgHM stored per year and the UB values are $60/kgHM and $5/kgHM stored per year. The NV for storage of FR

29 Gao, Fanxing and Won Il Ko, Korea Atomic Energy Research Institute, Economic Analysis of Different Nuclear Fuel Cycle Options, Science and Technology of Nuclear Installations, Hindawi Publishing Corporation, Volume 2012, Article ID 293467.

30 U.S. DOE, Energy Information Agency, Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants, April 2013.

31 Gao, Fanxing and Won Il Ko, Korea Atomic Energy Research Institute, Dynamic Analysis of a Pyroprocessing Coupled SFR Fuel Recycling, Science and Technology of Nuclear Installations, Hindawi Publishing Corporation, Volume 2012, Article ID 390758.

metal SNF are $90/kgHM and $7.5/kgHM per year. LB values are $60/kgHM and $5/kgHM per year and UB values are $240/kgHM and $20/kgHM per year. These values are based on those provided as input to the SMAFS model and summarized in NEA 2006.

A.4 Spent Fuel Dry Storage Unit Costs

This study assumes a unit dry storage cost for UO_2 SNF with a NV of $150/kgHM; a LB unit cost of $100/kgHM, and an UB unit cost of $250/kgHM. For dry storage of HLW resulting from pyroprocessing of UO_2 SNF and FR metal SNF, a NV of $120,000/kgHM is assumed along with a LB value of $80,000/kgHM and UB of $200,000/kgHM. These unit costs are consistent with the values identified in NEA 2006.

A.5 Reprocessing Unit Costs

Based on the analysis of the cost for pyroprocessing LWR SNF in Section 4.5, this study assumes a NV for pyroprocessing UO_2 SNF of $1,218/kgHM. The LB value is assumed to be $500/kgHM and the UB - $2,500/kgHM.

A recent study from researchers at KAERI identified a single cost for pyroprocessing and FR metal fuel fabrication (NV: $5,000/kgHM, LB: $2,500/kgHM, UB: $7,500/kgHM), but did not identify the portion of these costs attributable to fabrication.[32] As noted above, using the ratio of fabrication costs to pyroprocessing costs in NEA 2006, the NV for FR metal pyroprocessing is $2,100/kgHM, with a LB of $1,100 kg/HM and UB of $2,500/kgHM.

A.6 Disposal Packaging Unit Costs

The SMAFS model includes assumptions for the unit costs for packaging of UO_2 SNF and HLW for disposal. Based on a comparison of the unit costs in the NEA study to the costs projected by the U.S. DOE for SNF packaging for the Yucca Mountain repository, it appears that the packaging costs in the SMAFS model include the cost of the disposal package as well as the costs associated with loading the waste package (repository surface facilities and loading operations). Based on a study conducted by researchers for the Electric Power Research Institute ("EPRI") in 2007, this study utilizes NV for UO_2 SNF disposal packaging of $200/kgHM, a LB value of $150/kgHM, and an UB value of $350/kgHM.[33]

The unit costs for packaging HLW from UO_2 and FR SNF from pyroprocessing are based on assumptions in NEA 2006. The unit costs for UO_2 HLW and FR HLW disposal

32 Gao, Fanxing and Won Il Ko, Korea Atomic Energy Research Institute, Economic Analysis of Different Nuclear Fuel Cycle Options, Science and Technology of Nuclear Installations, Hindawi Publishing Corporation, Volume 2012, Article ID 293467.

33 Electric Power Research Institute, An Economic Analysis of Select Fuel Cycles Using the Steady-State Analysis Model for Advanced Fuel Cycle Schemes, Report 1015387, December 2007.

packaging assumes a LB of $100,000/m3 of HLW; a NV of $200,000/m3 of HLW; and a UB of $400,000/m3 of HLW.

A.7 Waste Disposal Unit Costs

Waste disposal costs include unit costs for disposal of low and intermediate level radioactive waste ("LILW"), short-lived ("SL") isotopes requiring near-surface disposal, LILW long-lived ("LL") isotopes requiring geological disposal, and SNF and HLW assuming deep geologic disposal. The SNF and HLW unit costs are captured using two separate parameters: one for the unit cost of disposal in $\$/m^{3,}$ and a second for the unit volume of earthen material that must be excavated for heat generating waste, expressed in m^3/kW.

The values for disposal of LILW-SL and LILW-LL wastes are consistent with those from NEA 2006. The LILW-SL unit costs assumed a LB of $1,200/$m^3$, a NV of $2,000/$m^3$, and a UB of $3,000/$m^3$. These LILW-SL disposal costs appear to be reasonable estimates that bound the range of disposal costs for near-surface disposal in the U.S.

The LILW-LL unit costs for cavern-based disposal assumed a LB of $4,000/$m^3$, a NV of $6,000/$m^3$, and a UB of 8,000/$m^3$. These values are consistent with estimates from other countries.

In a 2007 study conducted by EPRI researchers, SNF and HLW disposal costs and parameters for the SMAFS model were developed based on information for the Yucca Mountain repository. The Yucca Mountain Final Environmental Impact Statement (FEIS) estimated the total excavated repository volume to be 4.4 million m^3. This study utilized the EPRI LB and NV for unit cost for SNF and HLW disposal galleries of $600/$m^3$ (LB) and $2,500/$m^3$ (NV). An UB value of $5,000/$m^3$ is used, double the NV. Regarding the unit volume of disposal galleries that must be excavated for heat generating waste, this study uses the LB and NV from the 2007 EPRI study which assumed a NV of 41 m^3/kW of SNF or HLW and a LB of $10 m^3/kW. The NV is based on a waste package thermal limit for Yucca Mountain, the estimated repository excavated volume and the amount of SNF to be disposed. This study assumes a UB of 100 m^3/kW (more than twice the NV).

A.8 Other Parameters

In addition to the unit cost parameters described above, the SMAFS model also includes the waste generation parameters described in Section 2. This includes LILW generated during the conversion, enrichment and fuel fabrication processes, during reactor operation, and during reprocessing operations. In addition, the SMAFS includes volumes of SNF and HLW resulting from the fuel cycle schemes considered. This study utilizes the waste management parameters from NEA 2006. Since NEA 2006 did not include a scenario in which UO_2 SNF is reprocessing using pyroprocessing, this study utilizes the waste parameters associated with reprocessing using a UREX process. The resulting parameters for FP, minor actinides, plutonium and reprocessed uranium utilized in this study are consistent with values for pyroprocessing of UO_2 SNF that are contained in recent studies such as a 2012 study conducted by researchers from KAERI[34] and a 2010 study by multiple authors that examined the economic and business case for pyroprocessing of UO^2 SNF.[35]

The SMAFS model includes an estimate of the activity, thermal output and neutron source for SNF and HLW associated with each fuel cycle. The SMAFS model includes values for the amount of time that SNF and HLW remains in interim storage and dry storage. There is an interim storage parameter that is tied to the amount of time SNF and HLW remain in interim storage prior to dry storage or further processing.

34 Gao, Fanxing and Won Il Ko, Korea Atomic Energy Research Institute, Economic Analysis of Different Nuclear Fuel Cycle Options, Science and Technology of Nuclear Installations, Hindawi Publishing Corporation, Volume 2012, Article ID 293467.

35 Archambeau, Charles, Blees, Change, Hunter, Shuster, Ware and Wooley, Economic/Business Case for the Pyroprocessing of Spent Nuclear Fuel (SNF), 100 Ton/Yr Pyroprocessing Demonstration Plant, November 2010.

Table A- 1 General Fuel Cycle, Reactor, Fuel Fabrication, and Reprocessing Unit Costs

Parameter Description	Lower Bound (1)	Nominal Value (2)	Upper Bound (3)	Unit
General				
Unit cost of natural uranium	90	156	390	$/kgU
Unit cost of depleted uranium	45	78	195	$/kgU
Unit cost of conversion	7	15	20	$/kgU
Unit cost of enrichment	80	120	175	$/SWU
Unit cost of storing depleted uranium	2.6	3.6	4.6	$/kgU
Unit cost of storing reprocessed uranium	2.6	3.6	40.0	$/kgU
Fixed charge rate for investment	6%	9%	12%	%/year
Fixed charge rate for D&D	8%	8%	8%	%/year
Annual Rx O&M costs (as fraction of capital cost)	3%	4%	5%	%/year
Reactors				
Unit cost of installed power PWR	4,500	5,600	6,500	$/kWe
Unit cost of installed power FR	3,000	5,400	6,400	$/kWe
Load Factor for PWR	85%	90%	95%	%
Load Factor for FR	80%	85%	95%	%
Fuel Fabrication				
Unit cost of UO_2-fuel fabrication	280	320	365	$/kgHM
Unit cost of FR-Metal fuel fabrication	1,400	2,900	5,000	$/kgHM
Reprocessing				
Unit cost of UO_2 Pyroprocessing	500	1,218	2,500	$/kgHM
Unit cost of FR-Metal fuel Pyroprocessing	1,100	2,100	2,500	$/kgHM

Table A- 2 SNF and HLW Transportation, Interim Storage and Dry Storage Unit Costs

Parameter Description	***Lower Bound (1)***	***Nominal Value (2)***	***Upper Bound (3)***	***Unit***
SNF And HLW Transportation				
Unit cost of UO_2 SNF Transportation	75	100	125	$/kgHM
Unit cost of FR Metal SNF Transportation	125	250	500	$/kgHM
Interim SNF Storage				
Unit cost of UO_2 SNF interim storage (fixed)	40	50	60	$/kgHM
Unit cost of UO_2 SNF interim storage (var. with time)	5	5	5	$/kgHM
Unit cost of FR-Metal SNF interim storage (fixed)	60	90	240	$/kgHM
Unit cost of FR-Metal SNF interim storage (var. with time)	5	7.5	20	$/kgHM
Dry Storage				
Unit cost of UO_2 SNF dry storage	100	150	250	$/kgHM
Unit cost of UO_2 Pyroprocessing HLW Dry Storage	80,000	120,000	200,000	$/m^3
Unit cost of FR PYRO HLW Dry Storage	80,000	120,000	200,000	$/m^3

Table A- 3 SNF and HLW Packaging and Disposal Unit Costs

Parameter Description	*Lower Bound (1)*	*Nominal Value (2)*	*Upper Bound (3)*	*Unit*
Packaging				
Unit cost of UO_2 SNF Packaging	150	200	350	$/kgHM
Unit cost of UO_2 PYRO HLW Packaging	100,000	200,000	400,000	$/m^3
Unit cost of FR PYRO HLW Packaging	100,000	200,000	400,000	$/m^3
Disposal				
Unit cost of LILW (short lived) near-surface disposal	1,200	2,000	3,000	$/m^3
Unit cost of LILW (long lived) cavern-based and geological disposal	4,000	6,000	8,000	$/m^3
Unit cost of disposal galleries for spent fuel (underground cost)	600	2,500	5,000	$/m^3
Unit cost of disposal galleries for HLW (underground cost)	600	2,500	5,000	$/m^3
Unit volume of disposal galleries that have to be excavated for heat generating waste	10	41	100	m^3/kW

APPENDIX B COMPARISON OF FUEL CYCLE COSTS FOR AN OT CYCLE AND FR CYCLE

Using the nominal unit costs for the fuel cycle parameters that are summarized in Appendix A, nominal total generation costs for an OT Cycle and FR Cycle are summarized in Table 3 and Table 12, respectively. The nominal equilibrium fuel cycle costs for these two fuel cycles are compared in Table B-1.

Table B- 1 Comparison of Fuel Cycle Costs for the OT Cycle and FR Cycle Using Nominal Front-End Unit Costs

Cost Component	Nominal Unit Cost	OT Cycle (mills/kWhe)	FR Cycle (mills/kWhe)
Uranium	\$156/kgU	3.2	2.0
Conversion	\$15/kgU	0.3	0.2
Enrichment	\$120/SWU	1.9	1.1
UO_2 Fuel Fabrication	\$320/kgU	0.7	0.5
Metal IFR Fuel Fabrication	\$2,900/kgHM		0.8
UO_2 Pyroprocessing	\$1,218/kgHM		2.2
IFR Pyroprocessing	\$2,100/kgHM		0.7
Waste Management	Appendix A	1.4	0.3
Total		7.5	7.8

The total calculated fuel cycle costs for the OT Cycle are 7.5 mills/kWhe compared to 7.8 mills/kWhe for the FR Cycle. In the OT Cycle, front-end fuel cycle costs account for 81% of the overall fuel cycle costs, with the remaining costs 19% attributed to waste management costs. In contrast, in the FR Cycle, which includes operation of LWRs and IFRs that supply Pu and minor actinides as feed for metallic IFR fuel, front-end fuel cycle costs (uranium, conversion, enrichment, UO_2 fuel fabrication) account for 49% of overall fuel cycle costs, metal IFR fabrication represents 10%, costs for pyroprocessing account for 37% and the remaining 4% of costs are attributed to waste management.

While not quantified as a potential cost savings in Table 14, the FR Cycle also consumes 194 kg of DU in the FR metal fuel used to produce 1 TWhe of electricity and the consumed DU will no longer require continued storage and eventual disposal.

Importantly, however, the total NV, LB and UB costs of producing electricity by way of the OT and FR Cycles are quite comparable. While the NV cost for the OT Cycle is 105 mills/KWhe compared to 104 mills/KWhe for the FR cycle.

APPENDIX C LIST OF ACRONYMS

Am	Americium
ANL	Argonne National Laboratory
BRC	Blue Ribbon Commission on America's Nuclear Future
Cm	Curium
DOE	U.S. Department of Energy
DU	Depleted uranium
EBR I, EBR II	Experimental Breeder Reactor I, II
EPRI	Electric Power Research Institute
FBR	Fast breeder reactor
FEIS	Final Environmental Impact Statement
FP	Fission products
FR	Fast reactor
FR Cycle	Fast reactor cycle
GWd/MTU	Gigawatt-days/metric ton of uranium
HLW	High-level radioactive waste
HM	Heavy metal
IFR	Integral fast reactor
INL	Idaho National Laboratory
KAERI	Korean Atomic Energy Research Institute
kgU	Kilogram of uranium
kgHM	Kilogram of heavy metal
kW	Kilowatt
kWhe	Kilowatt-hour electric
LA	License application
LB	Lower bound
LILW-LL	Low- and intermediate-level waste – long-lived
LILW-SL	Low- and intermediate-level waste – short lived

LMFBR	Liquid metal fast breeder reactor
LWR	Light water reactor
m^3	Cubic meters
MOX	Mixed oxide
MTHM	Metric tons heavy metal
MTU	Metric tons of uranium
MWe	Megawatt-electric
Np	Neptunium
NPP	Nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NV	Nominal value
NWF	Nuclear Waste Fund
NWPA	Nuclear Waste Policy Act, as amended
O&M	Operation and maintenance
OT Cycle	Once-through cycle
Pu	Plutonium
PWR	Pressurized water reactor
ROI	Return on investment
SMAFS	Steady-State Analysis Model for Advanced Fuel Cycles Schemes
SNF	Spent nuclear fuel
SWU	Separative work unit
TBq	Terabecquerel

TWhe	Terawatt-hours electric
UB	Upper bound
U_{irr}	Irradiated uranium
UF_6	Uranium hexafluoride
UO_2	Uranium dioxide
UOC	Uranium ore concentrates
U.S.	United States
W	Watts